

V. CONCLUSION

CONCLUSION

It is widely agreed in the lithography community that at-wavelength interferometric testing is a fundamental requirement in optical system evaluation. As advances in circuit fabrication technology press the field toward shorter wavelengths and ever-tighter optical tolerances, nowhere are the metrology challenges now as great as for EUV. After several years of work in the development of EUV interferometry as a part of the ongoing research in EUV lithography and related technologies, the success and utility of this research have been amply demonstrated.

Following initial measurements of high-resolution EUV Fresnel zoneplate lenses which revealed the limitations of the conventional point diffraction interferometer, a novel, more sophisticated and improved *phase-shifting* point diffraction interferometer was developed. The latter design was implemented for the at-wavelength measurement of a lithographic-quality EUV 10× Schwarzschild objective. These studies showed nearly diffraction-limited characteristics of the low-spatial-frequency wavefront aberrations, accompanied by a high density of mid-spatial-frequency defects in the multilayer coatings.

Overcoming experimental difficulties necessitated the development of several new interferogram-analysis phase-retrieval methods. Problems in controlling the phase-increment used in phase-shifting analysis were overcome by the development of a novel approach, called the *Fourier-Transform Method of Phase Shift Determination*. This general method improves the accuracy of phase-shifting analysis considerably by using the phase of the Fourier-domain first-order peak to determine the relative phase-increments, eliminating the common problem of fringe print-through.

The presence of the defects posed significant complications for the data analysis, especially the phase-unwrapping. The concept of guided unwrapping used in sub-Nyquist interferometry was successfully adapted to this problem in a novel approach called the *Fourier-Transform Guided Unwrap*. First, a low-spatial-frequency approximation to the unwrapped wavefront is found using the Fourier-transform method with strong spatial-filtering. The approximation is filtered strongly enough to bridge obstructions or localized regions of invalid data. The approximate wavefront is then used as a *guide* to properly unwrap the raw phase data, preserving all of the original high-spatial-frequency content.

A third new technique is a variation of the well-established method of Gram-Schmidt orthogonalization used for wavefront surface fitting to the Zernike circle polynomials. The improvement enables the calculation of an important polynomial basis transformation matrix without the necessity of performing a matrix inversion operation.

Used in the rapid alignment of the interferometer, the *Fourier-Transform Alignment Method* developed and implemented by the author simplifies the difficult task of positioning a 100-nm pinhole onto the

center of a sub-200-nm focused EUV beam. Using the measured diffraction pattern, or an interferogram recorded by the CCD, the Fourier-transform is rapidly computed, scaled, and displayed, revealing the intensity pattern of test and reference beams in the image-plane. With a continuously-updating display, the two beams can be positioned much more easily than is possible without this tool.

In an effort to evaluate the performance of the interferometer and to characterize the error sources, measurement precision was investigated in a variety of ways. Each individual experiment was designed to isolate (as well as possible) the effects of a single component of the system or of a specific measurement configuration. These experiments reveal that the most significant contributors to measurement uncertainty are the 100-nm-scale reference pinholes used to generate the spherical reference wavefronts. Yet measurements that sought to *intentionally* induce random errors by displacing the reference pinhole far from the optimum position were only able to create small RMS wavefront differences, on the order of 0.02 waves. Every other component performed significantly better than this.

The pinholes are the most critical elements of the PS/PDI, and the ultimate performance will be limited by their quality. Measurement uncertainties show that the quality of the reference wave is affected by the aberrations of the optical system under test. Thus, the importance of adequate spatial filtering increases with the magnitude of the aberrations in the test system. At the time these experiments were conducted, adequately small reference pinholes were not available. The pinholes used were not smaller than 130 nm; yet studies here indicate that the optimum pinhole size for providing adequate spatial-filtering without sacrificing intensity transmission should be below 100 nm.

As a qualitative verification of accuracy, the Schwarzschild objective was used in a series of imaging experiments. Favorable comparisons of the resolution-test-pattern images with the predicted performance indicate that the systematic measurement errors must be small in comparison to the measured wavefront.

The first direct quantitative measurements of significant chromatic aberrations near the 13.4-nm peak wavelength of the Schwarzschild objective's multilayer coatings demonstrate both the importance and sensitivity of at-wavelength inspection. Interferometric wavefront measurements provide detailed quantitative information about broad areas of the surface in ways that high-accuracy reflectometry cannot.

Future work. While the development of high-accuracy and high-precision EUV interferometric capability may meet or exceed the requirements of EUV lithography, its existence cannot guarantee that optical fabrication and multilayer deposition technologies will reach *their* target specifications. One of the most challenging issues is the mid- to high-spatial frequency roughness present in the substrates and multilayers, causing an unacceptable amount of scattering.

As part of this dissertation research, studies have been made to evaluate the relative merits of dif-

ferent configurations of the PS/PDI interferometer. These studies include estimates of the relative efficiencies. With the required development of high power EUV sources for lithography may come the opportunity to create *in situ* EUV interferometry, allowing precision focusing and system alignment to be performed on a production-level tool in a fabrication environment. The high efficiency of the PS/PDI interferometer, the accuracy it provides, and the ease and reliability of the data analysis relative to competing designs make the PS/PDI a candidate for such an *in situ* inspection tool.

The concurrent development of state-of-the-art visible-light interferometry capable of achieving measurement tolerances in the same range as EUV interferometry (Sommargren 1996a, 1996b) meets the current need for a test that can be performed during the optical fabrication process and before the deposition of multilayer coatings. Eventually, comparisons of EUV and visible-light measurements of the same optical systems will yield substantial information about the properties of the multilayer coatings. Yet the investigations of this thesis indicate that at-wavelength testing will probably never be displaced entirely: the multilayer response depends critically on wavelength and other properties that cannot be reliably measured with visible-light.

There are several important areas of research that require more careful investigations, beyond the scope of this thesis. Accuracy is by far the most prized attribute of an interferometric system. The development of routine null-testing (via two-pinhole tests, or by other means) to quantify the systematic error contributions and to establish the accuracy limits is an essential component of reliable interferometry and must be integrated into future interferometer designs.

Further investigations of pinhole diffraction, both experimental and theoretical, are essential to the continued development of point diffraction interferometry. It may be discovered that some absorber materials simply function better than others in generating the reference wave. Also, controlling the thickness of the absorber may be a way to achieve high wavefront quality where small pinholes are unavailable. Determining the optimum pinholes size for the measurement of optical systems with NA higher than 0.1 is another challenging area of research; the compromise between transmitted intensity, wavefront quality, and fabrication issues yields many unanswered research questions.

Continued development of the PS/PDI spatial-filter window-and-pinhole geometry may yield improved measurement schemes suited to a variety of optical systems. Certain design optimizations can simplify the experimental apparatus or facilitate the identification and removal of geometrical systematic errors.

Relevant to the adaptation of the PS/PDI to a compact laser-plasma EUV source are experiments that investigate the relationship between measurement uncertainties, noise, and flux requirements. These experiments can be performed using the synchrotron source with limited exposure times.

Closing remarks. It is my sincere hope that the investigations presented in this dissertation will establish a framework for future research on the PS/PDI or related interferometers. The studies of Chapter 5, in particular, are intended to identify the most important systematic measurement effects in a way that is as general and accessible as possible. The material presented here may aid in identifying the most important design issues for the application of the PS/PDI to the measurement of an arbitrary optical system — be that an EUV optical system with sub-nanometer fabrication tolerances, or a radio telescope with square-meters of collection area. The new methods of interferogram analysis and wavefront surface fitting are very general and may find useful application in a wide range of interferometric systems.

Independent of the status of EUV lithography as a candidate technology for mass-production, the research described here may create new opportunities for the evaluation of high-resolution systems at short wavelength. The high degree of coherence that has been demonstrated in these measurements also reflects favorably on future experiments with coherent EUV radiation using a high-brightness synchrotron light source.